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PROPERTIES OF FIBER COMPOSITES FOR ADVANCED FLYWHEEL ENERGY STORAGE DEVICES

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The performance of commercial high-performance fibers is examined for application to flywheel power supplies. It is shown that actual delivered performance depends on multiple factors such as inherent fiber strength, strength translation and stress-rupture lifetime. Experimental results for recent stress-rupture studies of carbon fibers will be presented and compared with other candidate reinforcement materials. Based on an evaluation of all of the performance factors, it is concluded that carbon fibers are preferred for highest performance and E-glass fibers for lowest cost. The inferior performance of the low-cost E-glass fibers can be improved to some extent by retarding the stress-corrosion of the material due to moisture and practical approaches to mitigating this corrosion are discussed. Many flywheel designs are limited not by fiber failure, but by matrix-dominated failure modes. Unfortunately, very few experimental results for stress-rupture under transverse tensile loading are available. As a consequence, significant efforts are made in flywheel design to avoid generating any transverse tensile stresses. Recent results for stress-rupture of a carbon fiber/epoxy composite under transverse tensile load reveal that these materials are surprisingly durable under the transverse loading condition and that some radial tensile stress could be tolerated in flywheel applications.

KEYWORDS: Fiber Composites, Flywheels, Stress-Rupture

1. INTRODUCTION

Although the concept of storing energy in a rotating mass is an ancient idea, the relatively recent advent of advanced fiber composite materials offers a potential for improved energy storage and conversion using rotating electromechanical devices. The achievable energy density (energy/weight) of a simple flywheel design, such as a circumferentially wound ring or cylinder, is proportional to the specific strength (strength/density) of the material. Although other designs have been suggested and constructed, this version is the most common for energy storage applications. As discussed in the earliest papers on the

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subject, such as the article by R. F. Post and S. F. Post (1), the proportionality between energy density and specific strength favors the use of fiber composites. The remarkable combination of mechanical properties and low density achieved with fiber composites has made them attractive and nearly essential for aerospace applications. Unlike these applications, which are driven primarily by a high stiffness-to-weight ratio, flywheels require a combination of high tensile strength and low density. The trade-off between maximizing the energy storage capability and establishing safe operating limits is probably the single most critical design problem in commercial flywheel applications. To overcome this problem, a thorough understanding of the failure mechanisms and long-term durability of the materials and flywheel structures is needed.

The class of materials known as fiber composites encompasses a wide variety of material types and forms. The common feature is the combination of high-strength and/or high-modulus fibers bound together by a matrix material. This paper discusses the specific case of continuous fibers in a polymeric matrix, which offer the highest specific strengths. The specific strengths of commercially available high-performance fibers are compared. However, differences in the translation of material strength into the flywheel structure as well as long-term performance can be over-riding concerns and both of these are discussed. New experimental results are presented for the stress-rupture lifetimes of a high-strength carbon fiber/epoxy composite loaded in both the longitudinal and transverse directions.

2. HIGH-PERFORMANCE FIBERS FOR ADVANCED FLYWHEELS

During the last ten years, there have been several material developments that have an impact on the design of flywheel energy conversion and storage systems. Carbon fibers with tensile strengths exceeding 6.2 GPa have been developed. Several new polymer fibers such as the new aramids Twaron and Technora, and the extended-chain polyethylene (PE) fibers Spectra and Dyneema offer impressive properties and very low density. A new rigid-rod polymer fiber, polybenzobisoxazole (PBO), developed at Stanford Research Institute and the Wright-Patterson Laboratory, is now available commercially under the trade name Zylon (Tyobo). The PBO fibers exhibit the same strengths and moduli as the new high-strength carbon fibers, but at a 12% lower density. A summary of tensile properties for high-performance fibers is given in Table 1. Many of these fibers are being used or considered for applications such as flywheels and pressure vessels, which require performance under long-term sustained or cyclic loading. However, the long-term lifetime data for many of these materials apparently doesn't exist or isn't available in the open literature.

The commercial fibers with the highest specific strengths are the PBO, PE, and high-strength carbon fibers as shown in Figure 1. However, the intrinsic specific strength of fibers is only one property that needs to be considered for flywheels in long-term applications. Translation of strength into composite structures, strength degradation under sustained loading, transverse tensile strengths, and creep are also important material concerns for durable rotor designs.

2.1 Composite Properties

2.1.1 Fiber Strength Translation In making the materials selection for any application of fiber composites, it is essential to consider the properties of the composite system and not just the fiber and matrix properties alone. Experience has shown that because of process-induced defects, reliable design data can only be obtained from tests on the as-fabricated composite structure. A good example of this is the measured fiber-direction tensile strengths of composite structures. While the manufacturer's impregnated strand test yields strength data for the fiber in a composite, it is usually greater than that achieved in structures. This disparity is due both to matrix effects and processing-induced defects. Typical 0° (fiber-direction) strength values for epoxy matrix composites are given in Table 2. For comparison purposes these values have all been normalized to 60% fiber volume fraction. These data reveal that only the carbon fiber composites exhibit more than 75% of the fiber strengths. The glass fibers exhibit the lowest degree of intrinsic fiber strength translation, which is indicative of how sensitive their strengths are to processing and handling. It is clear that for comparison of specific strengths and the corresponding energy density capacity of high-performance fibers, one must look at actual composite properties to obtain reliable data.

Although very high strengths have been reported for pure glass fibers at cryogenic temperatures, the tensile strengths of E-glass composites with epoxy and cyanate ester resin systems were found to be only 1.3 and 1.7 GPa, respectively, at –197°C (8). Similar results were found for unidirectional S2-glass composites (9), which exhibited at most 2.3 GPa tensile strength even though the average strength of the filament at this temperature is reported to be an astonishing 8.3 GPa (10). Apparently, for glass fiber the strength translation generally falls far short of what would be expected based on single filament tests.

2.1.2 Composite Durability For energy storage, flywheels will be spun at high speeds for long periods of time. If a system designed for a 10-year lifetime was discharged once a day, the resulting 3,650 cycles would not constitute a significant fatigue history.

Although the combination of sustained loading at speed and even a small number of cycles can have a synergistically undesirable effect, it is the behavior under the constant load condition that is more pertinent to energy storage flywheel systems. This tensile stress-rupture lifetime behavior of fiber composites was studied most extensively during the flywheel programs of the 1970s and 1980s. The largest materials database was accumulated by the Lawrence Livermore National Laboratory for the behavior of Kevlar-49, E-glass, S-glass, and AS4 carbon fiber impregnated strands. Further results for the stress-rupture lifetimes of more modern high-strength carbon fibers have been obtained and will be discussed in the following section.

The degradation of composite strength under sustained loads is due to both fiber and matrix contributions. It is not clear which dominates, but comparison of data for filaments and impregnated strands offers some clues. Single filaments of carbon appear to be much more resistant to stress-rupture than the strand counterpart (11). Dry bundles of E-glass also appear to be more resistant to stress-rupture than epoxy- and polyester-impregnated strands (12). While these facts demonstrate that there is a matrix contribution, the different stress-rupture lifetime behavior for impregnated strands having the same matrix but different fibers clearly shows the significant fiber contribution to the long-term response (13). Based on these observations, it can be concluded that the stress-rupture behavior is dependent upon the properties of both constituents.

The large body of work on stress-rupture of fiber composites has been mostly limited to fiber-direction (0°) loads. In thick flywheels there will also be significant radial tensile stresses, which act along the transverse (90°) direction of the composite. The transverse strength is a matrix/interface-dominated property and is in the range of only 34–83 MPa—nearly two orders of magnitude less than 0° strengths. Little data exists for the stress-rupture behavior in the transverse direction; consequently, most flywheel designs seek to minimize radial tensile stresses and avoid premature failure in this weak mode.

Many solutions to reduce the high radial tensile stresses in thick fiber composite flywheels have been proposed. The preferred condition would be to maintain a compressive radial stress at maximum spinning speed, because there is little experimental data to guide selection of a tensile radial stress which can be tolerated for long times. Several techniques for producing radial compressive stresses have been proposed and applied to fiber composite flywheels. These include: programmed tension during filament winding, interference fits between concentric cylinders, bonding of concentric cylinders using an adhesive that is pressurized during cure, mass-loading the inner diameter, and building the flywheel using materials that provide a gradient in specific modulus from a low value at the inner diameter to high value at the outer diameter. Despite the potential advantages of these techniques, they all have their own limitations and drawbacks. For example, there are limitations to the amount of residual stresses that can be incorporated by programmed tension in the filament-winding process. There are also limitations in the specific modulus gradient that can be produced using available materials. Since it is difficult to eliminate all radial tensile stresses in flywheel designs, experimental results are needed for the transverse stress-rupture behavior of composites. Preliminary results were obtained for a composite system based on a high-strength carbon fiber and an epoxy matrix.

3. EXPERIMENTAL

All stress-rupture tests were conducted with a prepreg material comprised of T1000G carbon fibers (Toray) and an epoxy matrix (ERL-1908, Amoco Performance Products). A towpreg based on a 12K (12,000 filament) tow of the T1000G fiber was used to fabricate specimens for longitudinal stress-rupture tests. Unidirectional tape of the same material was used to fabricate 90_{16} laminates for transverse stress-rupture tests. The towpreg was cured into both flat ribbons and rods that had a circular cross-section and a diameter of 0.66 mm. The latter were made by threading the tow through polyolefin heat-shrink tubing and collapsing the tube around the uncured tow. During cure, the tow was tensioned using weights to ensure that the filaments were well-collimated and straight. All materials were autoclave-cured following the manufacturer's recommendations to yield a nominal fiber volume fraction of 60%. Specimens for transverse tests were machined from the laminated panels using a cut-off saw equipped with a diamond wheel and flood coolant. Specimens were 2.54 cm wide by 25.4 cm long and were gripped to provide a gage length of 15.2 cm using bolted aluminum plates and pieces of 400 grit abrasive paper. This gripping method has been shown to yield the best results for static transverse strength of unidirectional carbon fiber/epoxy composites (14). Both the flat ribbons and circular cross-section rods of the cured towpreg were tested for static strength. The fiber is reported to have a tensile strength of 6.38 GPa and due to the high loads required to fail the 12K tow, there were difficulties encountered in testing the flat ribbons to avoid premature failures within the grips. An effective gripping method was developed for the circular rods by bonding them with Hysol EA 9396 adhesive to bolted aluminum plates. The composite rods were placed into matching semi-circular grooves, 0.64 mm in diameter, that were pressed into the aluminum plates using a hardened steel rod. Cured rods, 25.4 cm in length, were bonded with a grip length of 6.35 cm into the aluminum grips by curing the Hysol adhesive for 1 hour at 66°C.

Static strength tests were performed at quasi-static rates using an MTS servohydraulic test system. All stress-rupture tests were performed at ambient conditions of temperature and humidity in custom-made frames under dead-weight loading. Stress-rupture lifetimes were recorded using timer switches that were placed under the weight stacks.

4. RESULTS

The static or intrinsic strengths of the T1000G/1908 composite in the longitudinal and transverse directions are summarized in Table 3. A Weibull distribution was used to analyze the data for the longitudinal strength and it appears to do an adequate job of capturing the variation of static strengths as shown in Fig. 2. An insufficient number of tests were run in the transverse direction to allow the same analysis for these strengths. The Weibull function is given by

$$P(x) = \exp\left[-\left(x/\beta\right)^{\alpha}\right] \qquad [1]$$

where *P(x)* is the probability of survival, β is the scale parameter, and _ is the shape parameter (11). The variable x is stress when the distribution is applied to intrinsic strength data and time when applied to stress-rupture lifetime data. Previous work reported shape parameter values of 21.7 and 22.8 for a lower-strength, IM6/epoxy composite (15). The lower value of β measured here for the T1000G system indicates that there is slightly more scatter in the intrinsic strength of this higher strength fiber.

Longitudinal stress-rupture data at stress levels of 92.2 and 87.1% (the percentage of the intrinsic strength) were collected over a period of nearly three years. The tests at the lower level were terminated in order to use the test stations for other studies. However, the tests at 92% are ongoing and to date 40% of the specimens have survived over 50,000 h (5.7 y). The lifetime data for the two stress levels as well as the intrinsic strength data are given in Fig. 3. Some of the specimens failed upon loading, which would-be expected for the stress levels examined. Using [1] with the Weibull parameters for intrinsic strength given in Table 3, it can be shown that the probabilities of immediate failure when loaded to 92.2% and 87.1% are 0.182 and 0.0838, respectively. For the number of tests conducted, this corresponds to nearly 6 loading failures at 92.2% stress and 2 at 87.1% stress, which agrees well with the number of observed loading failures (6 and 3, respectively) for the two stress levels. A time of 0.001 h was used as an estimate for the lifetimes of specimens that failed immediately upon loading in the stress-rupture frames.

The durability of the material at the lower, 87% level (three failed during loading, two failed at longer times, 20 survived more than 20,000 h) indicates that appreciable stress-rupture degradation of this high-strength carbon fiber may only be active for stress levels within the range of intrinsic strengths. A useful comparison is made with the stress-rupture behavior of other high-performance fibers in Fig. 4. For simplicity, only the 50% lifetime lines are plotted and it should be noted that since only 20% of the T1000G specimens failed at the 87% level, the datapoint shown in Fig. 4 is highly conservative. With this in mind, it is clear from Fig. 4 that carbon fibers are much more resistant to stress-rupture degradation than other high-performance fibers and that the higher strength T1000G carbon fiber is more durable than the AS4 carbon fiber. Some of the differences shown in Fig. 4 might be attributable to the matrix materials, but reported results discussed earlier for composites having different fibers and the same matrix material suggest that the matrix effect is secondary.

The Weibull parameters obtained for the lifetime distributions of the T1000G/1908 composite are summarized and compared with results for a standard strength (AS4) carbon fiber/epoxy composite in Table 4. The lifetime scale parameters show that higher strength T1000G fiber is more resistant to stress-rupture failure, but the shape parameters show that the results for this fiber are more widely scattered than for the AS4 material. These results for the higher strength fiber compare favorably with those reported for another high-strength carbon fiber (15) and they suggest that resistance to stress-rupture degradation may increase with intrinsic strength.

The results for stress-rupture testing in the transverse direction for four stress levels up to nearly 20,000 h duration are shown in Fig. 5. Also shown in this figure are the 50% failure line and the intrinsic strength results. The 50% probability line is drawn through the data at a stress level of 43% even though none of the specimens failed at this level. It is obvious that there is a strong stress-rupture degradation effect transverse to the fiber direction. However, for stresses at or below 40% of the intrinsic value (which corresponds to 24 MPa for this material), there appears to be a substantial lifetime.

5. DISCUSSION

In this paper, fiber composite materials and their relevant properties for flywheel energy storage applications were discussed. Commercially available high performance fibers were surveyed for specific tensile strength, fiber-to-composite strength translation, and behavior under sustained loading. Strength translation and the behavior under sustained loads are critical to the performance in long-term rotor applications. The choice of materials for flywheel energy storage applications is bracketed by the two extremes of performance versus cost.

Based on specific fiber tensile strength alone, the high-strength carbon and PBO fibers are the best candidates for high energy density flywheels. When strength translation into composite structures is considered, it appears that carbon fibers have the advantage. It has also been shown that carbon fibers have superior stress-rupture behavior and new results reported here for a high-strength carbon fiber composite indicate that higher intrinsic tensile strength leads to increased resistance to stress-rupture. To our knowledge, the stress-rupture behavior for the PBO fiber has not been characterized. Considering that it is spun from highly acidic solutions in a process similar to that used to make Kevlar fibers, there is a chance that the PBO fiber could suffer from the same sensitivity to moisture. A significant drawback with both carbon and PBO fibers is cost; prices usually range from $30 to over $150 per kilogram.

The cost of E-glass fiber composites is typically one to two orders of magnitude less than the other high-performance fibers. But this material and other glass composites suffer from inefficient fiber strength translation and degradation under stress-rupture conditions. The exceptional tensile properties of glass filaments that are measured in low-temperature, low-humidity environments demonstrate a large potential for improved composite performance in these lost-cost materials. The strength of pristine S2-glass filaments is reported to be as high as 11.6 GPa at liquid nitrogen temperature (10). However, data reported for strengths of E-glass and S-glass composites at cryogenic temperatures are far less than what would be expected based on filament strengths. Little is known about the stress-rupture behavior of these composites in low-temperature and dry environments. Since the strength of glass is controlled by the corrosive effects of water acting at surface flaws, both the strength and stress-rupture lifetimes are improved by either immobilizing the moisture at low temperature or eliminating the water in a dry environment (21). However it may not always be cost-effective to operate a flywheel energy storage system under such conditions. One approach to improving the strength translation and the stress-rupture lifetimes of glass fibers at ambient conditions is through the use of coatings. Studies of optical fibers have shown that extremely high strengths can be achieved at ambient conditions if the surface of the fiber is first dried and hermetically sealed with metal coatings (22). While this approach appears intriguing, issues such as cost and the thickness and composition of the coating to provide both optimum strength translation and fiber-matrix adhesion would have to be carefully evaluated.

The transverse tensile strength of fiber composites is relatively poor and the transverse stress-rupture behavior has not been well-characterized to date for any of the materials considered. Consequently, rotor designs usually incorporate some mechanism for reducing radial tensile stresses, but it is not always possible to eliminate them completely. Data presented herein for one carbon fiber/epoxy material show that the resistance to stress-rupture in the transverse direction, although much less than for the longitudinal direction, can be significant at stress levels less than half the intrinsic transverse strength. Thus it appears that some radial tensile stress can be tolerated under sustained loading in composite flywheels.

6. ACKNOWLEDGEMENTS

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Table 1. Tensile properties of high-performance fibers

Fiber	Density (g/cc)	Tensile Modulus (GPa)	Tensile Strength (GPa)	Manufacturer
T700 Carbon	1.80	228	4.83	Toray
T1000G Carbon	1.80	297	6.38	Toray
E-Glass	2.58	72	3.45	OCF
R-Glass	2.55	85	4.33	Vetrotex
S2-Glass	2.49	87	4.59(1)	OCF
Hollex	1.80	67	3.45(1)	OCF
Fused Silica	2.20	69	3.45	J. P. Stevens
Kevlar 49	1.45	120	3.62	DuPont
Kevlar 29	1.44	58	3.62	DuPont
Twaron	1.44	80	3.15	ENKA
Twaron HM	1.45	124	3.15	ENKA
Technora	1.39	70	3.04	Teijin
Spectra 900	0.97	117	2.68	Allied-Signal
Spectra 1000	0.97	173	3.12	Allied-Signal
Dyneema	0.97	87	2.70	Dyneema VOF
Zylon-HM	1.56	269	5.80	Toyobo

(1) Measured using single filament test, all others using impregnated strand test.

Table 2. Typical 0° tensile strengths of epoxy-based fiber composites

Fiber	0° Tensile Strength (GPa)	Fiber Strength Translation(1) (%)	Test Method	Reference
T700 Carbon	2.66	92	Coupon(2)	2
T1000G Carbon	3.03	79	Coupon	2
E-Glass	1.02	49	Coupon	3
E-Glass	1.03	50	ASTM D3039	4
E-Glass	0.80	39	NOL Hydro(3)	3
E-Glass	0.95	46	Rotor Spin(4)	3
S2-Glass	1.79	65	ASTM D3039	4
S2-Glass	1.81	66	ASTM D3039	5
S2-Glass	1.53	56	NOL Hydro	3
S2-Glass	1.63	59	Rotor Spin	3
Kevlar 49	1.38	64	Coupon	6
Kevlar 49	1.52	70	NOL Hydro	3
Kevlar 49	1.47	66	Rotor Spin	3
Spectra 900	1.09	68	Coupon	7
Spectra 1000	1.36	73	Coupon	7

(1) Ratio of strength of fiber in composite to values given in Table I.
(2) Test details not specified, presumably similar to ASTM D3039.
(3) Navy Ordinance Lab hydrostatic burst of rings test.
(4) Thin-rim flywheel rotor burst test.

Table 3. Intrinsic longitudinal and transverse tensile strengths of T1000G/1908.

Test Direction	Average Strength (MPa)	Weibull Parameters		Number Tests
		Shape $\alpha\,(\sigma)$	Scale β (MPa)	
0°	3,735	14.73	3,870	25
90°	60.2 (CV = 7.7%)	—	—	8

Table 4. Weibull parameters for lifetime distributions of the longitudinal tensile stress-rupture of two carbon fiber/epoxy composite materials.

Fiber	Epoxy Matrix	Weibull Lifetime Parameters		
		Stress Level (%)	Shape $\alpha\,(t)$	Scale $\beta\,(h)$
T1000G	ERL-1908	92.2	0.14	5.94E3
		87.1	0.085	1.164E10
AS4[1]	DER-332/ T-403	91.3	0.18	5.68
		84.8	0.26	1.72E3

[1] Data taken from Reference (19).

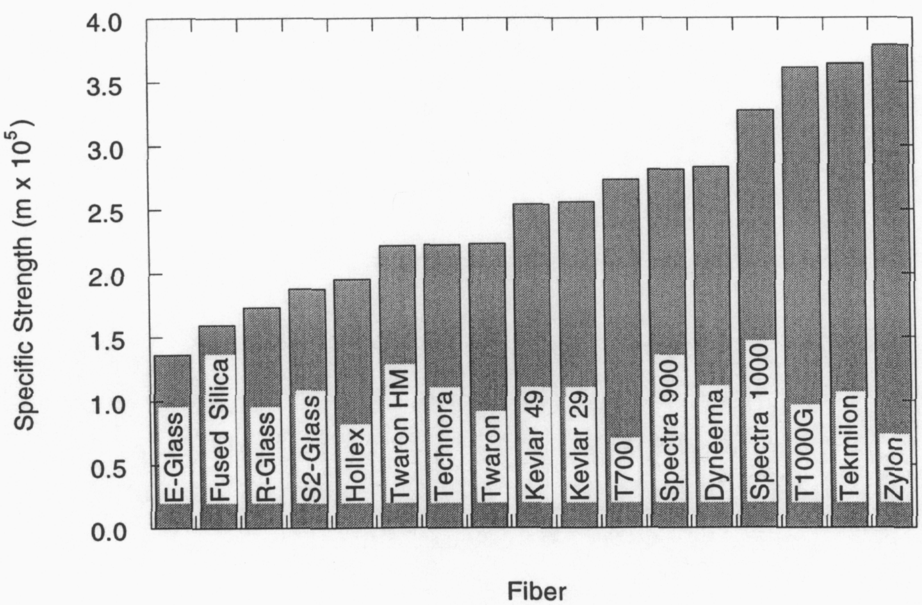

Figure 1. Specific strengths of high-performance fibers.

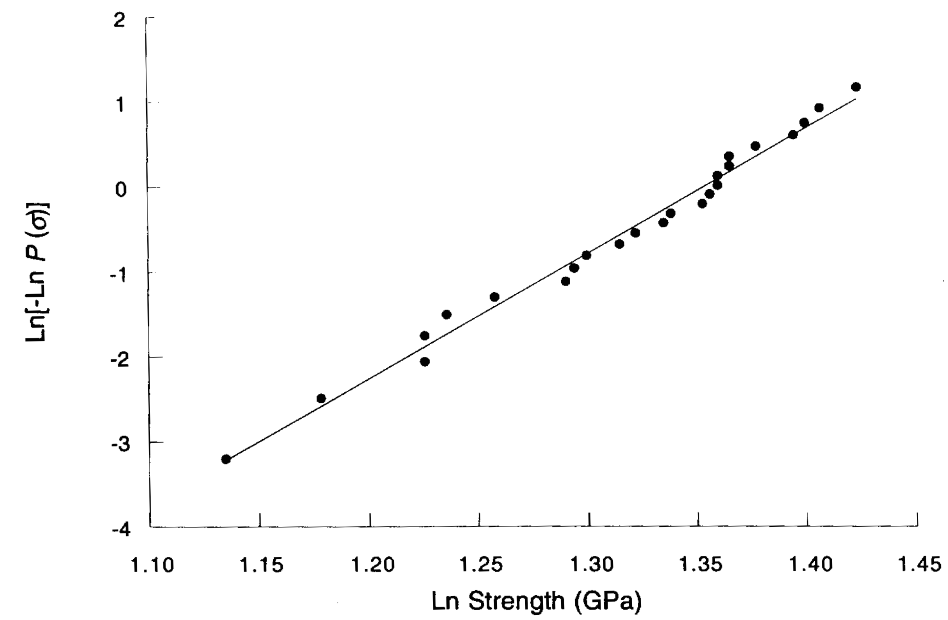

Figure 2. Intrinsic longitudinal tensile strength distribution for T1000G/1908.

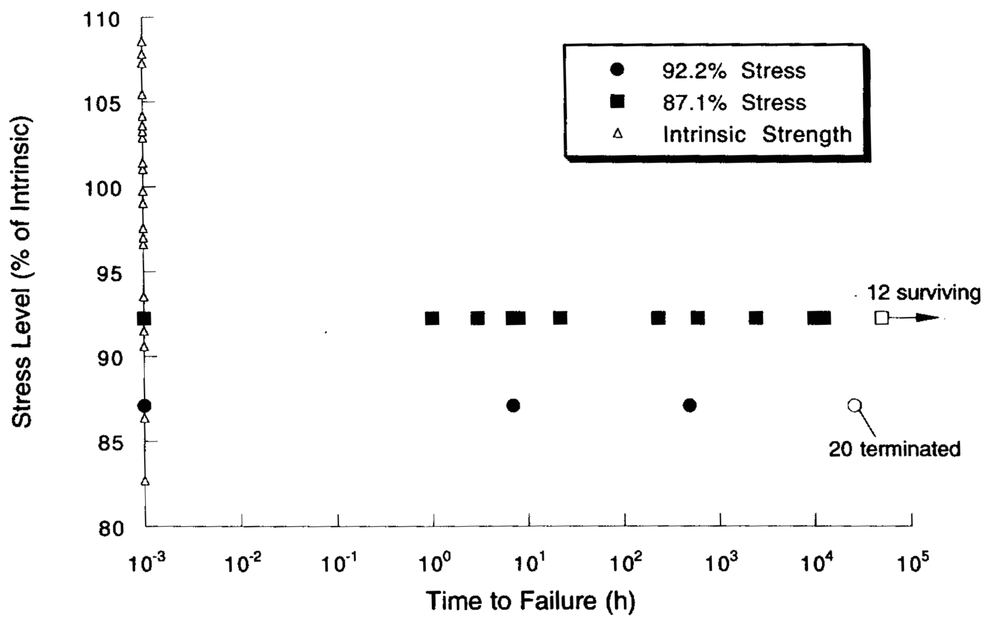

Figure 3. Stress-rupture lifetimes for longitudinal tension of T1000G/1908.

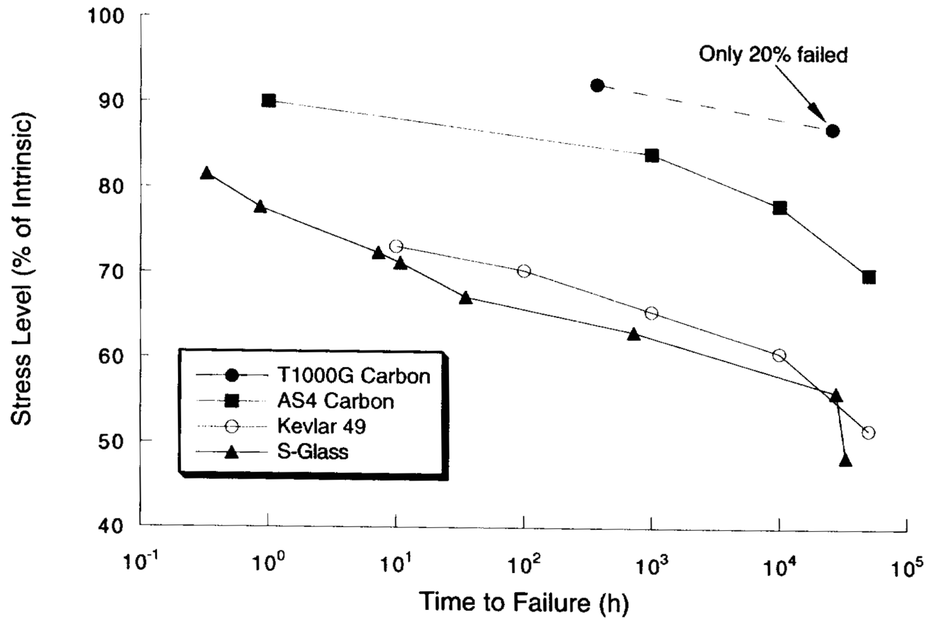

Figure 4. 50% probability lifetime lines for stress-rupture of different high-performance fibers (16–20).

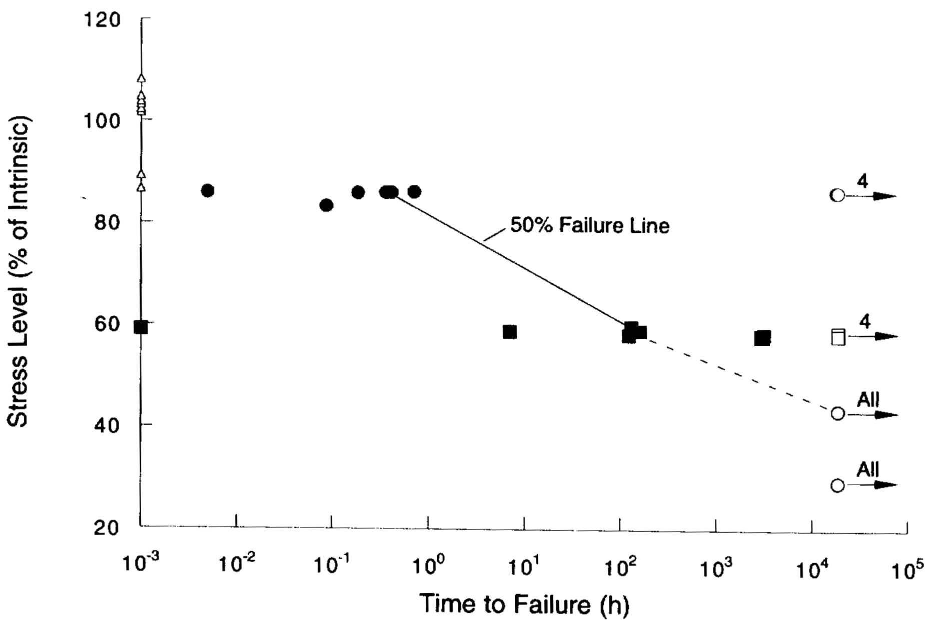

Figure 5. Strèss-rupture lifetimes for transverse tension of T1000G/1908.